

Measuring current by counting electrons in a nanowire quantum dot

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We measure current by counting single electrons tunneling through an InAs nanowire quantum dot. The charge detector is realized by fabricating a quantum point contact in close vicinity to the nanowire. The results based on electron counting compare well to a direct measurements of the quantum dot current, when taking the finite bandwidth of the detector into account. The ability to detect single electrons also opens up possibilities for manipulating and detecting individual spins in nanowire quantum dots.

A highly-sensitive charge detector is a powerful tool for probing electronic properties of mesoscopic structures. In contrast to conventional transport measurement, the system under investigation does not need to be connected to leads. This makes the measurement technique low-invasive and allows charge transitions within the nanostructure to be investigated [1]. By adding time resolution to the detector, tunneling of individual electrons can be detected in real-time [2]. This provides the possibility to extract statistics for the tunneling electrons and to probe electron-electron correlations [3, 4], as well as for determining electron spin dynamics [5, 6].

Another possible application of time-resolved charge detection is to use it as a metrology standard for current. Bylander *et al* experimentally verified the fundamental relation $I = e f$ by relating a highly-correlated current I through an array of tunnel junctions to the frequency response f of a single-electron transistor [7]. In this work, we combine a quantum dot (QD) formed in a semiconductor nanowire with a quantum point contact (QPC) acting as the charge detector. The large energy scales of the nanowire QD enable operation at $T = 4$ K and allow the QPC to be operated at larger bias voltages compared to GaAs QDs [8]. This together with the high sensitivity of the detector make time-resolved single-electron detection possible in a regime where we can simultaneously measure the QD current with a conventional current meter. In this way, we count electrons one by one and make direct comparisons to the measured current. We find that the current measured by counting is lower than the one measured with conventional techniques. The difference can be quantitatively accounted for by considering the electrons missed because of the limited bandwidth of the charge detector, which is a known quantity [9].

InAs nanowires are catalytically grown by metal-organic vapor phase epitaxy (the detailed recipe is described in [10]). An InAs nanowire is deposited on top of a shallow (37 nm) AlGaAs/GaAs heterostructure based two-dimensional electron gas (2DEG). The QD in the InAs nanowire and a QPC in the underlying 2DEG are defined in a single etching step using patterned electron beam resist as an etch mask. This method guarantees

perfect alignment as well as strong coupling between the two devices [11].

Figure 1(a) shows a scanning electron microscope (SEM) image of a device similar to the one used in the measurements. The QD is defined by the etched constrictions in the nanowire between S and D. The QPC is formed between the two etched trenches that separates it from the rest of the 2DEG. The regions marked by L and R are used as side gates to control the QD population and to tune the coupling between the QD and the source and drain leads. In the experiment, the QPC was biased with a DC voltage of $V_{\text{QPC}} = 1$ mV. In addition, a voltage was applied to the 2DEG on both sides of the QPC to compensate for the shift in QPC potential when changing the voltages on gates L, R. The bias of the QPC was kept smaller than the single-level spacing of the QD to avoid QD excitations due to photon absorption [8]. The measurements presented here were performed at a temperature of 1.7 K, but we have tested that the setup produces similar results at $T = 4$ K.

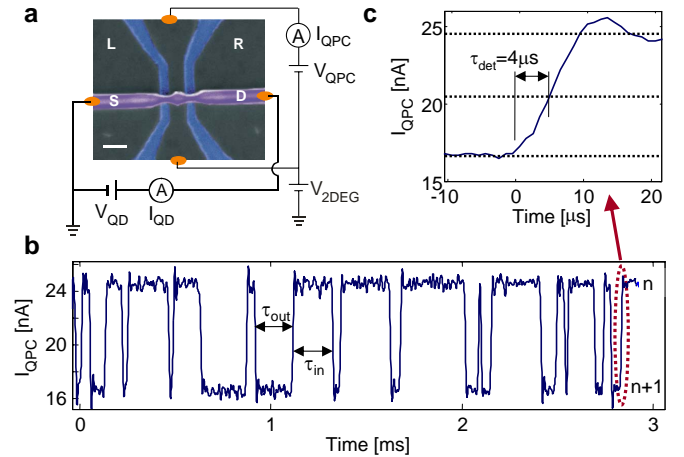


FIG. 1: (color online) (a) SEM image of the device. The quantum dot is formed in the nanowire, with the quantum point contact located in the 2DEG directly beneath the QD. (b) Typical time trace of the QPC conductance, showing a few electrons tunneling into and out of the QD. The upper level corresponds to a situation with n electrons on the QD. (c) Rise time of the detector, defined as the time needed for the current to cross the midline between current levels belonging to the n and $n+1$ electron states.

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The charge detector is implemented by operating the QPC at the slope below the first plateau and continuously monitoring its conductance [12]. Due to strong electrostatic coupling between the QD and the QPC, an electron entering or leaving the QD will shift the QPC potential and thereby change its conductance. Figure 1(b) shows a typical example trace of the QPC current. Coulomb blockade prohibits the QD to hold more than one excess electron. The two current levels in the figure corresponds to n and $n + 1$ electrons on the QD, respectively. Transitions between the levels relate directly to an electron tunneling into or out of the QD [13, 14, 15]. The times τ_{in} , τ_{out} describe the times needed to tunnel into and out of the QD. The change in QPC conductance when adding an electron to the QD is around 30 %. This is large change compared to most top-gate defined GaAs QDs, where the relative QPC conductance change is typically around one percent [14, 16].

The comparatively large signal allows us to increase the bandwidth of the detector. Figure 1(c) shows the rise time of the detector signal. Setting the threshold for event detection in the middle between the two levels, we find that the detector has a time resolution of $\tau_{\text{det}} = 4 \mu\text{s}$. The time scale corresponds to a maximal detectable current of $\sim e/(4\tau_{\text{det}}) \sim 10 \text{ fA}$; tunneling occurring on a faster timescale can not be resolved by the detector. In the present setup, the bandwidth is limited by the low-pass filter due to the capacitance of the cables between the sample and the room-temperature amplifier. The bandwidth can be greatly enhanced by using a cold amplifier [17] or an rf-QPC setup [16, 18, 19].

To characterize the system, we first tune the tunneling rates to be much slower than the time resolution of the detector. Figure 2(b) shows Coulomb diamonds measurements for the QD, measured by counting electrons from traces such as the one shown in Fig. 1(b). The large charging energy ($E_C = 12 \text{ meV}$) is due to the small size of the QD. In the regime of single-level transport, the tunneling times $\tau_{\text{in/out}}$ are expected to follow an exponential distribution

$$p_{\text{in/out}}(t)dt = \Gamma_{\text{in/out}}e^{-\Gamma_{\text{in/out}}t}dt. \quad (1)$$

Figure 2(b) shows the measured distribution of the tunneling times, taken at the point marked by I in Fig. 2(a). The solid lines are fits to Eq. (1), with $\Gamma_{\text{in}} = 640 \text{ Hz}$ and $\Gamma_{\text{out}} = 220 \text{ Hz}$.

In Figs. 2(c, d), we plot the separate tunneling rates $\Gamma_{\text{in/out}}$ for the upper part of the middle diamond in Fig. 2(a). Going upwards along the dashed line in Figs. 2(c, d), the Fermi level of the source lead is raised while the potential of the drain and the QD is kept constant. At $V_L = -1 \text{ mV}$ (marked by an arrow in the figure), there is a distinct step in Γ_{in} as the source lead is raised above an excited state of the QD. At the same time, the rate for tunneling out measured along the same line stays constant. We attribute this to fast relaxation of the excited state, so that the tunneling out process always occurs through the QD ground state [20]. The

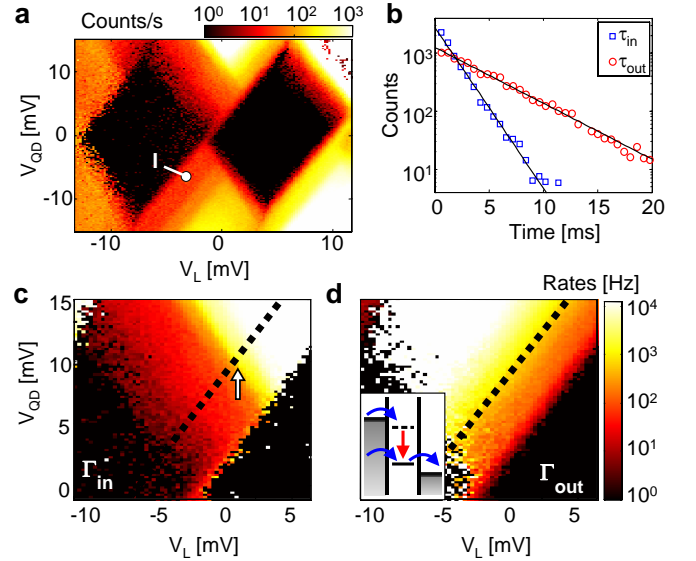


FIG. 2: (color online) (a) Coulomb diamonds measured by counting electrons entering and leaving the QD. To compensate for changes in the QPC potential, we set $V_R = V_L - 50 \text{ mV}$ and $V_{2\text{DEG}} = 0.7 V_L + 177 \text{ mV}$. (b) Distribution of tunneling times, taken at the position marked by I in (a). The solid lines are fits to Eq. (1) in the text, with fitting parameters $\Gamma_{\text{in}} = 640 \text{ Hz}$ and $\Gamma_{\text{out}} = 220 \text{ Hz}$. (c, d) Γ_{in} , Γ_{out} for the upper-middle part of (a). The arrow in (c) mark the position where an excited state enters the transport window. The inset of (d) depicts the energy levels of the system at the position marked by the arrow in (c).

situation is depicted in the inset of Fig. 2(d). The results of Fig. 2 demonstrate the stability and high level of control in the system and prove that the electron tunneling detected by the QPC originate from a QD formed in the nanowire.

In the following, we present measurements in a regime where the barriers between the QD and the leads are opened up to allow the QD current to be measured with a conventional current meter. Figure 3(a) shows the count rate for the positive bias part of a Coulomb diamond. In this regime, the ground state of the QD is weakly coupled to the source lead. The measurement shows equilibrium fluctuations between the QD and the drain lead [region I in Fig. 3(a, c)], but almost no counts inside the region marked by II. As the bias is further increased, the first excited state is available for transport and the count rate is increased (region III). Figure 3(c) displays the current through the QD for the same region as in (a), measured with a conventional current-to-voltage (I-V) converter. We only see current inside the regime corresponding to region III in Fig. 3(a). This is expected since the current measurement in contrast to the charge detector is directional; charge fluctuations between the QD and the drain lead as depicted in region I of Figs. 3(a, c) will not contribute to a net current flow. The discrepancies between the counting and current signal in the upper-right corner of Figs. 3(a, c) are due to the limited time resolution

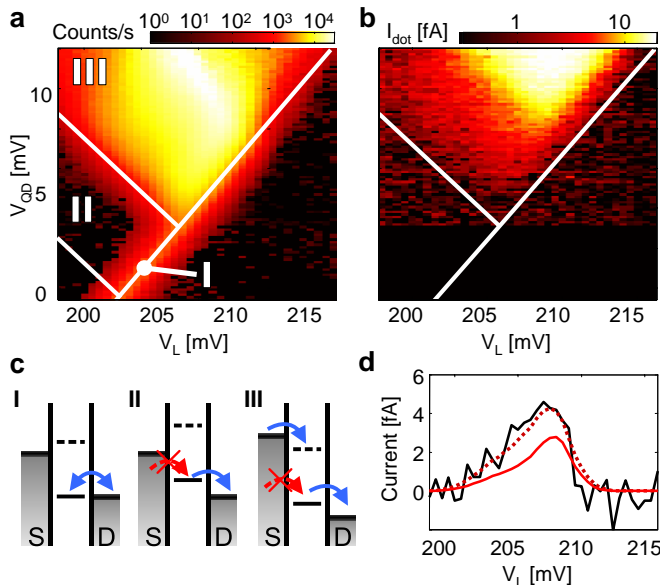


FIG. 3: (color online) (a) Electron count rate, measured with the QD in a more open regime. (b) QD current for the same region as in (a), measurement with a conventional current meter. (c) Energy level diagrams for the three regions marked in (a). In I, the count rate is due to equilibrium fluctuations between the QD and the drain lead. In region II, transport is blocked due to weak coupling between the QD ground state and the source lead. In III, a more strongly coupled excited state is available for transport and the current through QD is strongly increased. (d) Cross section of the colormaps in (a,b), taken at $V_{QD} = 7.1$ mV. The black curve is the current measured with current meter, while the gray is measured by counting electrons. The dashed line is the counting signal when compensating for the limited bandwidth of the detector.

of the detector; a second excited state entering the bias window makes the tunneling-in rate exceed the detector bandwidth.

In Fig. 3(d), we plot the QD current together with the electron count rate for fixed bias on the QD ($V_{QD} = 7.1$ mV). The count rate has been converted to current using $I = e/(\tau_{in} + \tau_{out})$. Even though the two curves show qualitatively the same behavior, the charge detector registers a current which is $\sim 30\%$ lower than the one measured by the I-V converter. We attribute the dif-

ference to the limited bandwidth of the charge detector. Tunneling events occurring on a timescale on the order of or faster than the time resolution of the detector are less likely to be detected, which modifies the measured statistics [9, 21]. However, knowing the detection time and assuming that Eq. (1) correctly describes the distribution of tunneling times, we can estimate the number of electrons missed by the detector. Following the ideas of Naaman and Aumentado [9], we find that the current is given by

$$I = e / \left((\tau_{in}^* + \tau_{out}^*) \left(1 - \tau_{det} \frac{\tau_{in}^* + \tau_{out}^*}{\tau_{in}^* \tau_{out}^*} \right) \right). \quad (2)$$

Here, τ_{in}^* , τ_{out}^* are average tunneling times extracted from the measurement. The results of Eq. (2) is shown as the dashed line in Fig. 3(d), with $\tau_{det} = 4 \mu s$ as extracted from Fig. 1(c). The current calculated taking the finite bandwidth into account agrees very well with current measured with the I-V converter. We emphasize that the curve does not include any free parameters, since the detection time is determined separately using the method shown in Fig. 1(c). It should be noted that the current measured by counting is determined with much higher precision than with conventional methods. The signal of the I-V converter was integrated for 10 s at each point, yielding a resolution of ~ 1 fA. Also, the signal had to be carefully compensated for amplifier drift. On the other hand, the counting signal was measured for 0.2 s, giving a standard deviation of only 70 aA.

We have demonstrated current measurements by counting electrons in a nanowire quantum dot. The insensitiveness to drift and the high precision of the counting procedure demonstrate big advantages of electron counting compared to conventional current measurement techniques. The measurements were performed at a temperature of 1.7 K, but the large charging energy and single-level spacing of the quantum dot allows operation even at $T = 4$ K. By incorporating the sample into a radio-frequency setup, we estimate that the detection bandwidth can be increased by at least three orders of magnitude [16, 18, 19]. Combining charge readout with fast gate-pulsing techniques opens up the possibility of investigating and manipulating individual spins in nanowire quantum dots [5, 6].

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